Jet Propulsion Laboratory
California Institute of Technology

Drilling mechanisms using piezoelectric actuators

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Background

- The use of drills as sampling tools is a precise method to acquire samples for addressing one of the most important questions in planetary exploration which is "whether we are alone in the universe", i.e. has ever life arisen anywhere else.
- Since water is a critical criterion for life-as-we-know-it, NASA prioritized the targets of future exploration missions to bodies in the Solar System that currently are known to have or have had flowing liquid water.
- In the most recent Planetary Decadal Survey (Vision and Voyages for Planetary Science in the Decade 2013-2022), Mars, Europa, and Enceladus were specifically called out for future exploration because of the accessibility to their aqueous regions.
- These bodies have the highest likelihood of having extant or extinct life and they require sample acquisition from below the surface.
- However, each of these bodies possesses its own unique drilling challenges.
- There are various commonalities among the strategies of drilling into these bodies including the requirements to penetrate the subsurface, capture samples, and present the unaltered sample to instruments for analysis.

Percussive drilling via piezo-actuation

- Drilling mechanisms are widely used for many applications including domestic, medical, industrial, military, geological and planetary ones.
- The drills are capable of penetrating a very large variety of materials.
- In extraterrestrial applications, we are generally limited by additional constraints not found on earth including power, volume, mass and limited pre-load.
- Increasingly, developers of drills to be used on other planetary bodies are seeking capabilities that address the complex challenges that are involved with the operation at extreme environments as needed for the in-situ exploration.
- The use of piezoelectric actuators offers effective capabilities of drilling particularly for operation in extreme environments.
- Over the last two decades, significant development has been made at the JPL's NDEAA Lab using piezoelectric actuation to perform percussive drilling where the formation under the bit cutting surface is fractured by impacts.
- The performance and cuttings removal is significantly enhanced by rotating the bit allowing the cuttings to be removed from the created borehole.
- This paper focuses on drilling mechanisms that are driven by piezoelectric actuators that have been developed in our laboratory.

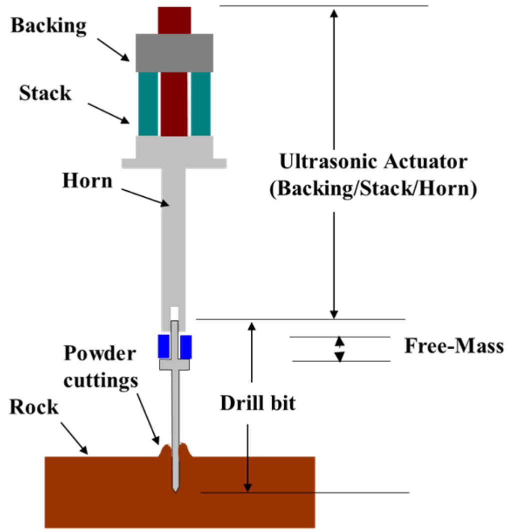
The Ultrasonic/Sonic Driller/Corer (USDC)

- Since 1999, we have been developing piezoelectric actuated drills that address the need for sampling mechanisms that can be operated at low gravity using low preload.

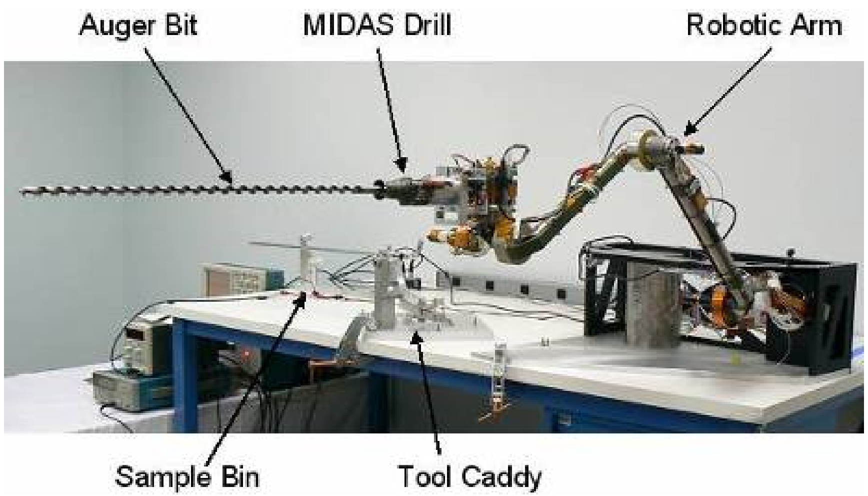
- Operating with low axial load allows for drilling from lightweight robotic platforms such as rovers.

- The first piezoelectric actuated drill that was developed is the ultrasonic/sonic driller/corer (USDC).

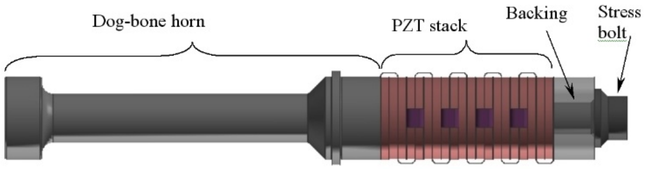
- It uses intermediate free-mass between the actuator horn and the bit converting high frequency vibrations to low frequency hammering.



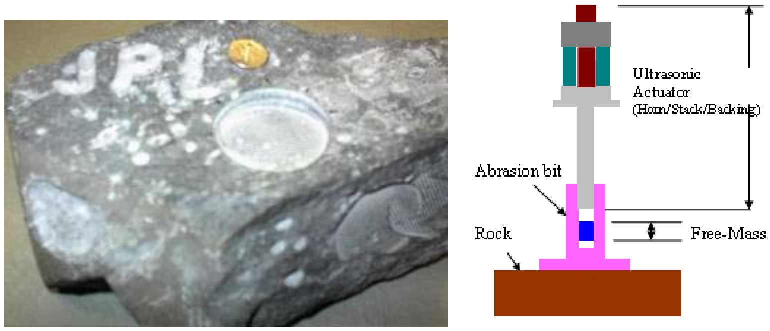
Novel USDC based mechanisms



Interchangeable bit mechanism

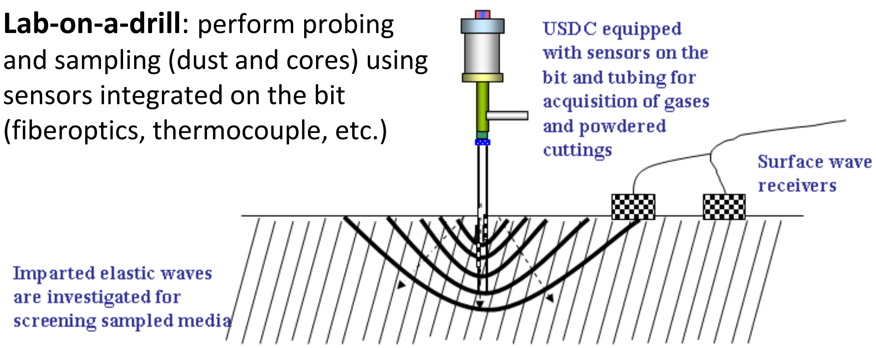


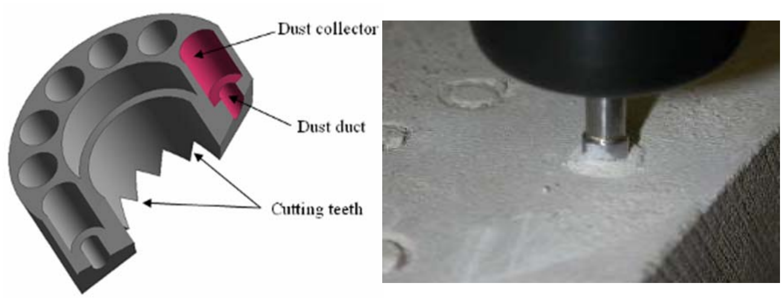
Dog-bone shape horn



Ultrasonic/Sonic Rock Abrasion Tool (URAT)

Lab-on-a-drill: perform probing and sampling (dust and cores) using sensors integrated on the bit (fiberoptics, thermocouple, etc.)

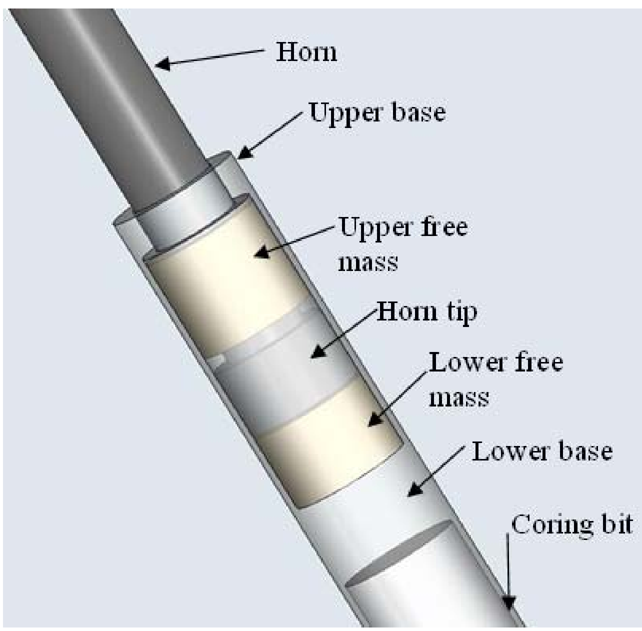


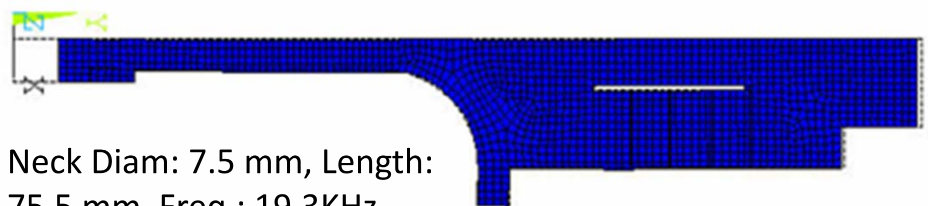


Novel bit for acquiring powdered cuttings

Dog-bone horn

The dog-bone horn offers in addition to the performance enhancement also design benefits as a mounting fixture.

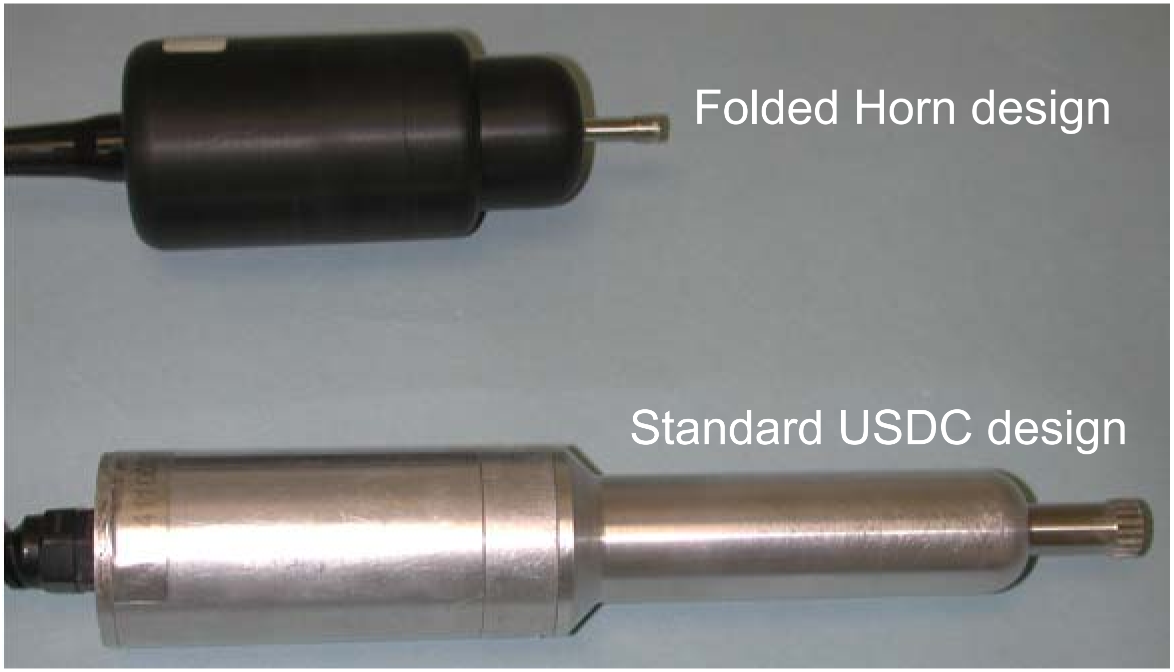


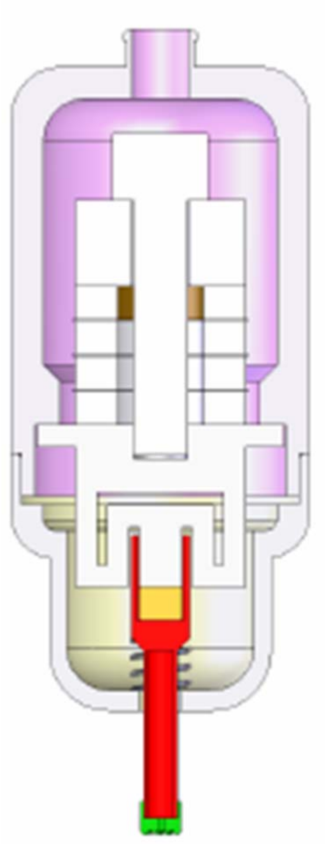


Neck Diam: 7.5 mm, Length: 75.5 mm, Freq.: 19.3KHz

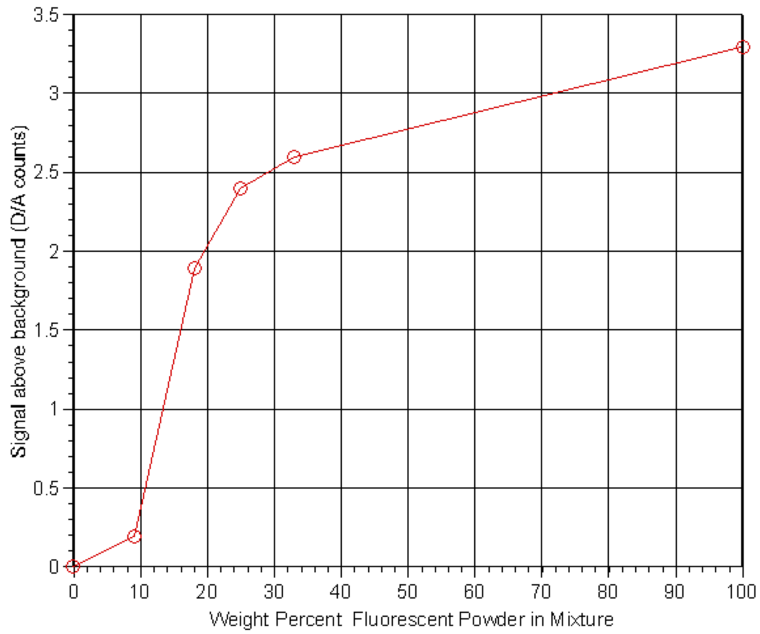
Dimensions reduction

Using a folded horn the length of the powdered cuttings sampler was significantly reduced.

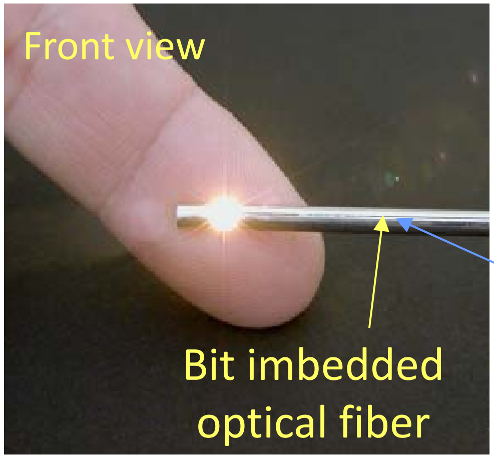




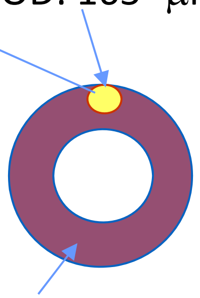
Integrated fiberoptics and measured reflectivity



Differential response in the range of 545nm and 700nm



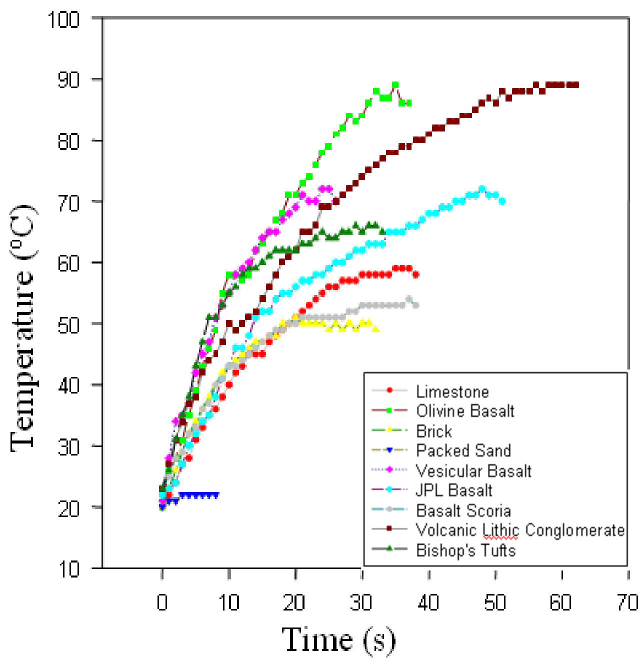
Optical fiber with coatings
OD: 165 -µm



Bit
OD: 3-mm
ID: 2-mm

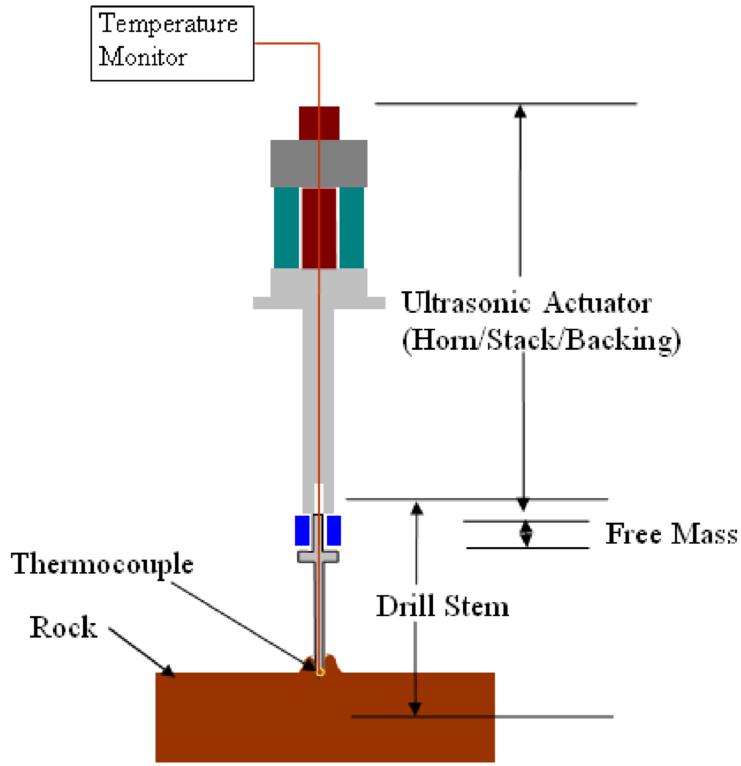
Bit Temperature measurements

A thermocouple was integrated into the USDC bit to allow real time monitoring the temperature during drilling.



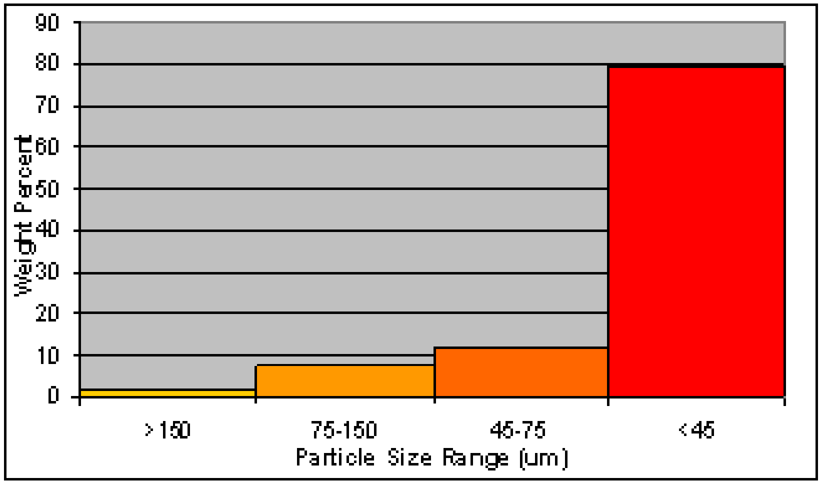
Temperature and maxima as a function of time for drilling variety of media

Power < 40 watts   Bit diameter = 3.6 mm

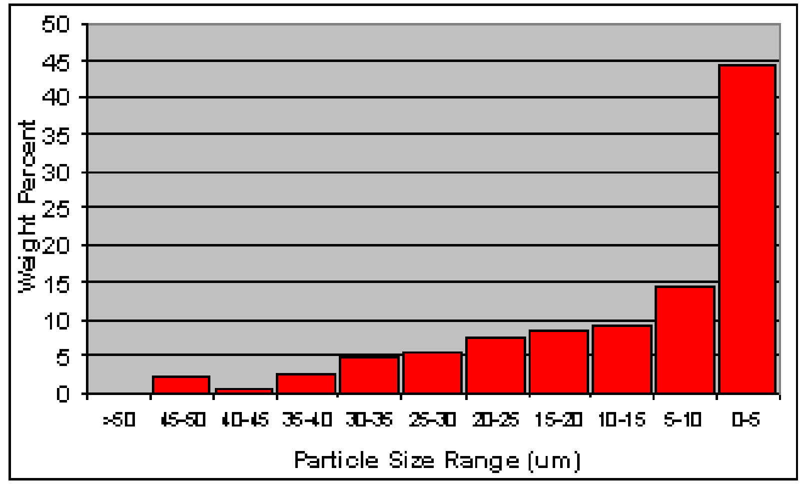


Experimental Setup

CHEMIN Sample #1 – Chinle Sandstone



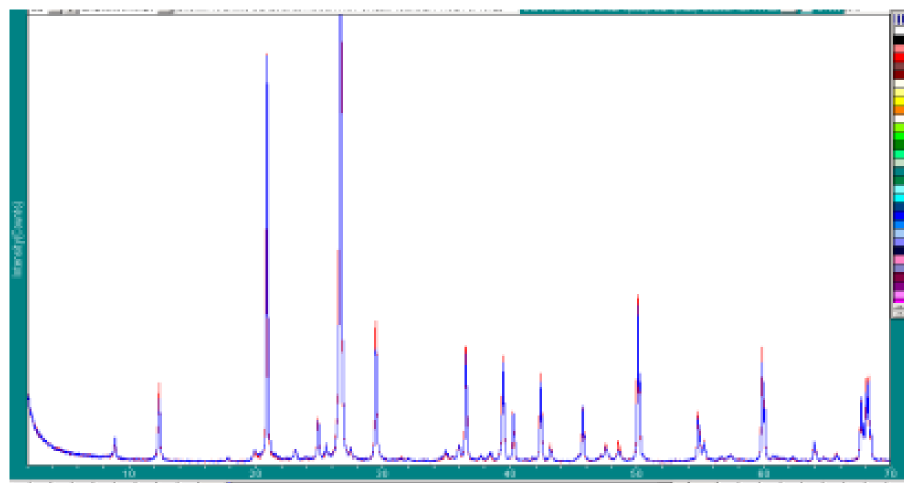
Size fractions obtained during wet sieving



Particle size distribution of the <45μm powder obtained using a Horiba CAPA-500 particle size distribution analyzer.

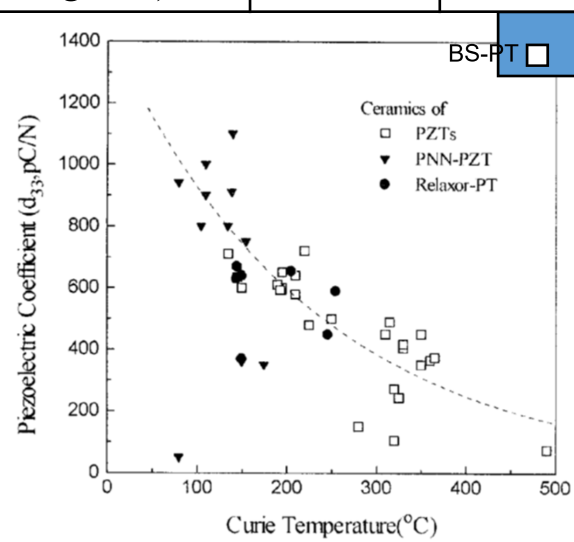
LANL's Lab XRD patterns of the <45 μ m USDC powder (blue) compared to the Retsch milled <5 μ m powder (red).

Note: The patterns compared extremely well.



Comparison of various Piezoceramics with $BiScO_3$–$PbTiO_3$

Material	Structure	T_c (˚C) (C/cm^2)	P_r	E_c kV/cm	d_{33} pC/N
PZT-5A (soft)	Perovskite (MPB)	330	36	~ 10–12	~ 400
PZT-8 (hard)	Perovskite (MPB)	330	25	> 15	~ 225
$PbNb_2O_6$ (modified)	Tungsten Bronze	~ 500	—	—	~ 85
$Na_{0.5}Bi_{4.5}Ti_4O_{15}$	Bismuth Layered	~ 600	—	—	18
$BiScO_3$– x$PbTiO_3$ x=62	Perovskite (rhombohedral)	420	28	17	290
$BiScO_3$– x$PbTiO_3$ x=64	**Perovskite (MPB)**	**450**	**32**	**21**	**465**
$BiScO_3$– x$PbTiO_3$ x=66	Perovskite (tetragonal)	460	23	25	260



Ref: T. Shrout, Penn State U.

The need for deep drill

- *The task has been focused on developing a deep drill for possible use in missions to Mars, Titan and Europa.*
  - In the Phoenix Scout and MSL, sample acquisition from 5 cm deep has been identified as a major challenge.
  - On such bodies as Mars, drilling 2 meters or more would allow acquisition of pristine samples from below the reach of harmful UV and surface radiation.
  - To be able to reach depths of hundreds of meters, the AG2 has been developed as a relatively light-weight and low power drill.
  - The goal of the Auto-Gopher-2 development was to demonstrate drilling up to 7 m depth in gypsum.

- *Auto-Gopher is a wireline rotary-hammer and it consists of:*
  - Piezoelectric actuator that hammers the bit and provides effective fracturing mechanism
  - Electrical motors that remove the cuttings via flutes on the bit, linear feed for weight-on-bit control, and anchoring

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Test of the ice-Gopher in Antarctica

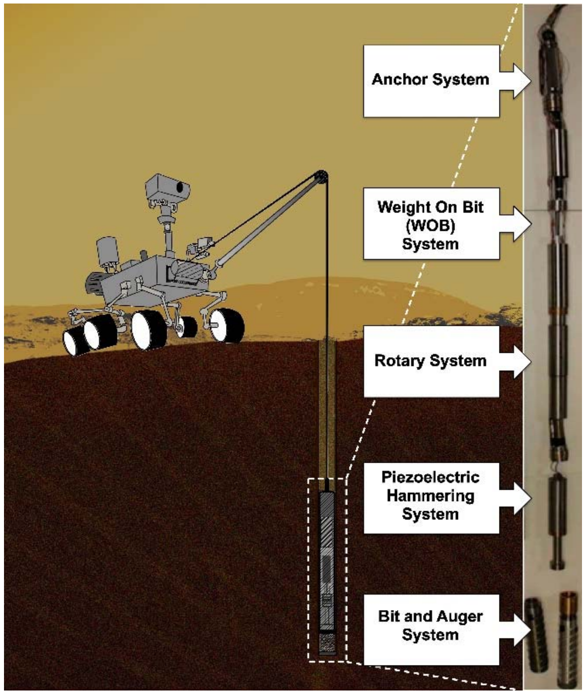
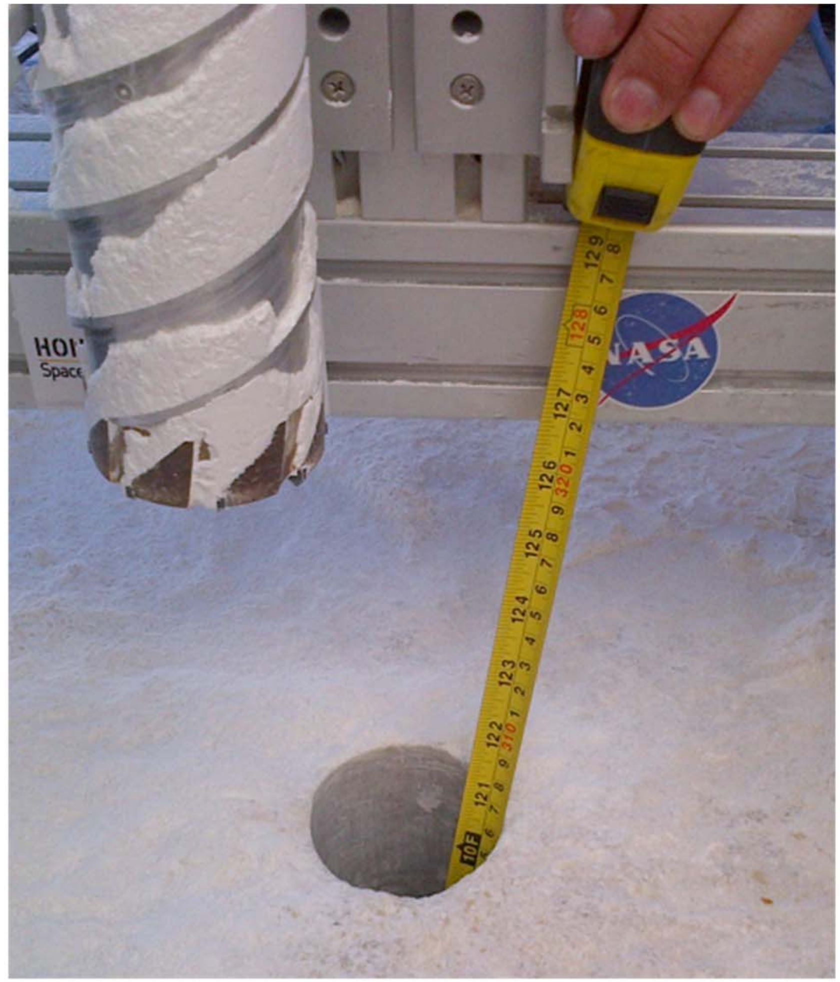


Illustration of the Auto-Gopher, concept as a wireline deep drill.

Lake Vida test site

The gopher at 176cm deep in Lake Vida

Field test of the Auto-Gopher-1



- 32 cores were extracted from a depth of 3.07 meter
- The experiment took three days and held November 2012

Auto-Gopher Background

- The main feature of the Auto-Gopher is its wireline operation where the drill is suspended on a tether with actuators, mechanisms, drive and control electronics that are built into a tube ending with a drilling/sampling bit.
  - The tether provides the mechanical connection to a rover/lander on the surface as well as power and data communication.
  - Upon penetrating a target incremental depth, the drill is retracted from the borehole, the collected cuttings removed, and the drill is lowered back into the hole to continue drilling.

- The heart of the developed drill is a vibratory mechanism driven by a piezoelectric transducer and its main attribute includes drilling various formations via low axial preload.

- The test results of the Auto-Gopher-1 indicated that such a drill can become an effective sampling tool for reaching great depths of many meters and beyond.

- The Auto-Gopher was developed jointly with Honeybee Robotics to support future *in-situ* NASA exploration missions, addressing the important question of whether life once existed or exists elsewhere in the solar system.

The Auto-Gopher-2 System

- Umbilical cable (3-in-1 solution: power, data, tether)suspension.
- The cable termination provides the mechanical and electrical interface between the drill and the tether - can support 5kN force.
- Power converters transform the 360V DC voltage to various intermediate buses.
- The anchors are self-contained modules to include their own actuators. They provide up to 8kN output force and can be synchronized together with the Z stage to provide the drill inchworm motion capability.
- Z-stage - high force capability of anchors and the Z-stage allow the drill to be unjammed in the borehole if necessary.
- The camera/sensor compartment includes a color CMOS camera and sensors for redundant slip detection.

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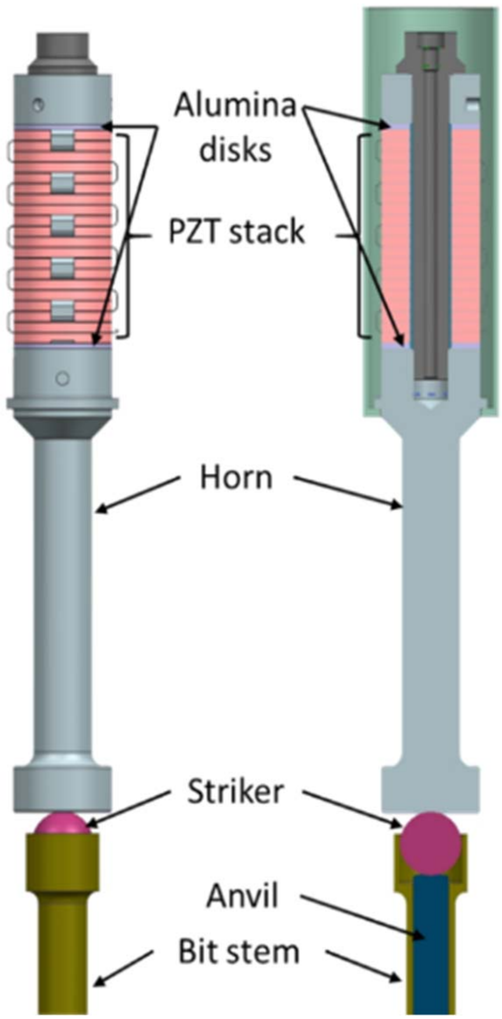
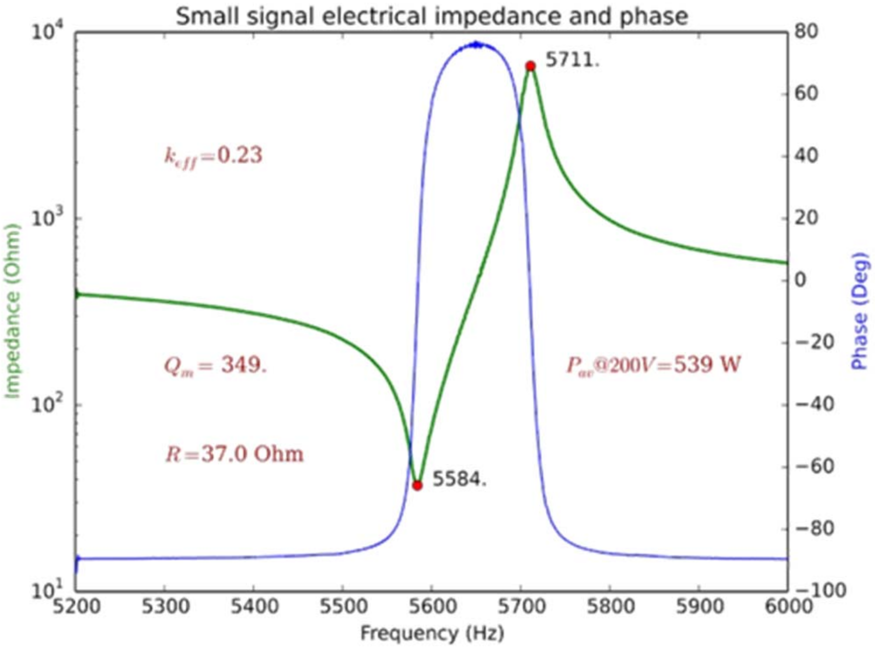
Transducer Development





Design, components, first fabricated prototype, impedance spectra

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Testing the hammering action

The actuator of Auto-gopher-1

Real time speed

x1/240

The actuator of Auto-Gopher-2

Real time speed

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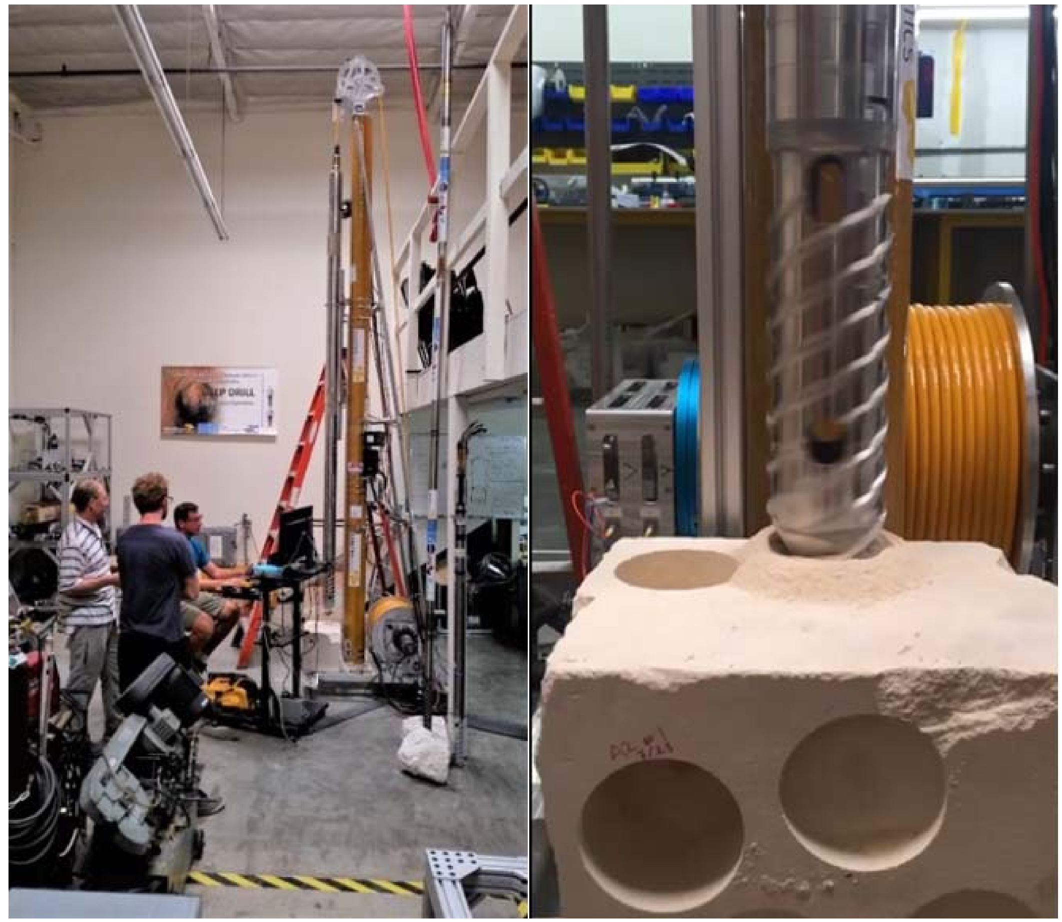
Laboratory testing

- The laboratory setup with drill bit, test limestone block and cable reel close-up.

- Soft – 25MPa Cordova Crème - used to test subsytems interaction
- Hard – 40MPa Indiana Limestone – closer to the field site strength and cryogenic ice – used to verify performance



Field test details

- Borrego Springs gypsum quarry (US Gypsum Company accommodations)
- Rock strength 39MPa +/- 2MPa
- Drive input parameters: Sweep Current 1000mA; Fuse Current 1500mA; Cycle Time ON 2 sec; Cycle Time OFF 1 sec (Duty Cycle 66%).
- Test duration >1 week

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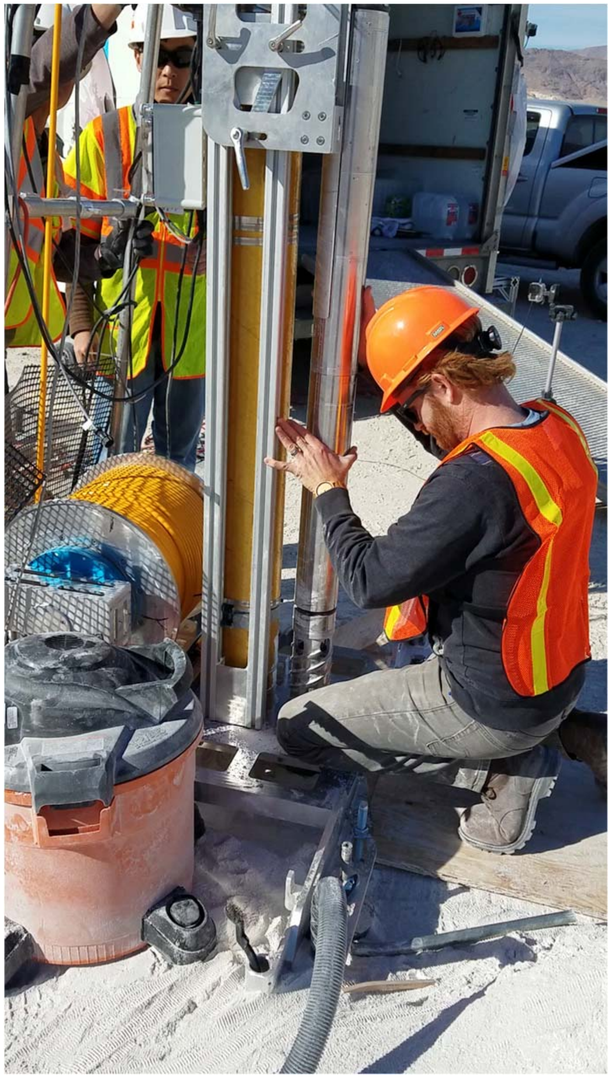
Field test location

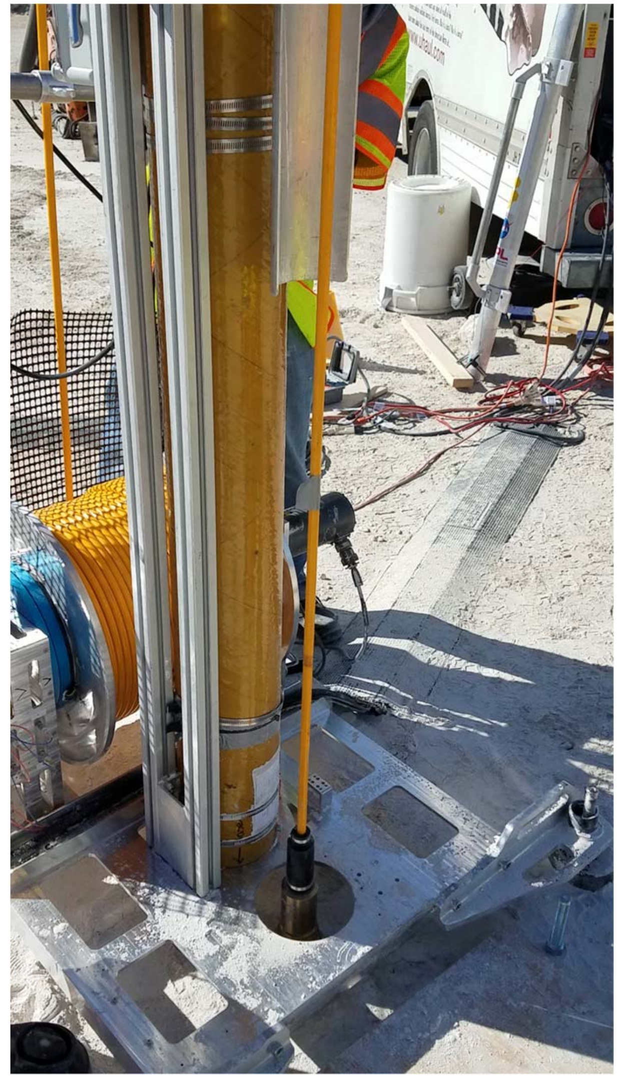
Field test

Field test with the drill fully inside the drilled hole (left), drilling operations during the day (middle) and night (right)

Field Test – reaching 7.52 m deep



Drill deployment



Drill extraction from the borehole

Conclusions and future work

- Presented the latest results in the development of the piezoelectric actuated drills where the technology was implemented into the Auto-Gopher-2.
  - A 5.2 kHz transducer was designed and fabricated;
  - drive electronics custom drive electronics to fit inside drill body and control software were developed;
  - Integrated into the drill system at Honeybee Robotics into the full developed drill system.
- With the development of Auto-Gopher-2, we demonstrated a scalable technology that will make deep drilling possible using current launch vehicles, power sources, as well as entry descent and landing (EDL) systems.
  - Power < 500 W
  - Mass 65 kg
  - Length 3.7m
  - Flight like umbilical cable
  - **Drilled 7.52m**, more than twice the drill's total length
- Yet to be solved/improved
  - Reduce size (length) and mass
  - Automatic drill bit unloading

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Acknowledgements

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